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Evaluation and Testing of Off-the-shelf Hall Sensors for Compliant Magnetic Field Measurement

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***Abstract** – Magnetic field measurements with a more than 6 decade dynamic range over a very extended frequency range are considered. This subject is getting nowadays more importance for compliance with the series of standards and regulations for human exposure to electromagnetic fields. ICNIRP and Video Display Terminal standards requirements in terms of field levels and bandwidth are translated into sensor specifications, which reveal to be very challenging. Furthermore, manufacturers' information is sometimes poor and doesn't allow easily engineers to design a fully compliant measuring equipment.*

***Keywords** – Magnetic measurements, Noise measurements, Hall devices*

I. INTRODUCTION

Over the recent years, the subject of human exposure to low frequency magnetic fields have been discussed thoroughly with different (and sometimes opposite) positions and opinions. While one may argue on long term effects and cumulative effects, there is a substantial agreement on limits for exposure based on "only established effects" (as clearly stated in [1]). ICNIRP statement [1] dates back to 1998 and it was definitely indicated as the reference publication by the EU Recommendation 519/99 [2] and by the National laws and regulations in the following years. ICNIRP guidelines have been integrated by an additional ICNIRP statement [3], dealing with transient (defined as "pulsed") and, in general, complex waveforms, processed in the time-domain. This subject and ICNIRP specifications are detailed in Section II.

A preliminary and thorough examination of measurement instruments available on the market confirmed that all instruments fail to comply to one or more of the following specifications (drawn from ICNIRP in Section II and reported here for clarity):

1) frequency range dc to 100 kHz (400 kHz if IEEE Std. 1140 Video Terminal Display standard is considered [4]);
2) range of amplitude values over more than 6 decades;
3) required sensitivity and accuracy;
4) analog output available for external sampling and post-processing.

Several industrial environments are characterized by multiple sources of emissions, with different magnetic field amplitudes and different frequency occupation. These aspects and the compliance with ICNIRP specifications produce hard to fulfill requirements for the measurement sensor and connected circuitry.

II. APPLICABLE STANDARDS AND LIMITS

Here limits and measurement methods are discussed, neglecting all other aspects concerning coupling mechanisms, biological effects and epidemiological studies.

A. Human exposure - ICNIRP

ICNIRP Guidelines indicate as basic restrictions for low frequency magnetic fields the amplitude of the induced current density in head and trunk (see Table 4 in [1]). From these basic restrictions, reference levels on measurable electromagnetic quantities (H and B field) are derived. ICNIRP distinguishes between occupational and general public (also indicated as residential) exposure limits.

Attention is focused on amplitude levels and frequency ranges, in order to derive specification for the Hall effect magnetic field sensor.

The frequency interval covered by ICNIRP for magnetic field with "induced electric fields and circulating electric currents" coupling mechanism is 1 Hz to 100 kHz. The B-field amplitude profile specified as limits over the entire frequency interval ranges between the maximum allowed value at 1 Hz for occupational exposure (L_{max}=200 mT) down to the minimum level for general public exposure at several kHz frequency interval (L_{min}=6.25 uT). The two curves are shown in Fig. 1.

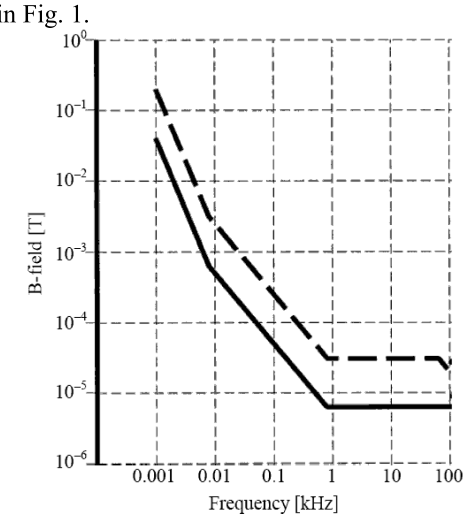


Fig. 1. ICNIRP B-field limits and related specifications

The 1 Hz values may be extended to DC as confirmed by the ICNIRP Guideline for static magnetic fields [5]; in this standard higher exposure levels are allowed for specific situations of temporary exposure or partial exposure.

ICNIRP B-field limits impose strict and hard-to-meet requirements on the Hall effect sensor, since they translate into a 200 mT (250 mT if a little over-range reading is needed) full scale, with a sensitivity requirement mDF (minimum Detectable Field) well below L_{min}. The required sensitivity may be estimated considering the mDF/L_{min} ratio, which gives directly the measurement accuracy in the worst case frequency interval (where the measured B-field levels are at minimum) and it may be fixed to1% or better. This hard requirement is quantified on the basis of the allowed noise for correct calculation of eq. (8) of ICNIRP (the sum of all normalized frequency components to be less than 1) as addressed in [6].

Taking into account the sensor itself and all the electronic circuits included for signal conditioning, a provisional mDF value of 0.1 to 1% of L_{min} is advisable; this value influences the minimum detectable field and in turn sensor accuracy at low field levels. So, the required B-field amplitude interval ranges for more than 6 decades from about 6/60 nT up to about 250 mT!

B. Video Display Terminals (VDTs)

The IEEE standard [4] gives sensors specifications and a specific method of measurement. This standard has been considered only as an "exercise", since it explicitly states that "the measurement probe shall consist of three mutually perpendicular concentric circular coils", so no chance for semiconductor sensors (in our case Hall effect based).

Besides the important element represented by an extremely high upper frequency (400 kHz), attention is focused on noise specifications: 40 nT for Band I and 5 nT for Band II, where Band I and II correspond to [5 Hz - 2 kHz] and [2 - 400 kHz] respectively. These broadband noise levels are very small indeed. The overall calibration uncertainty is specified to be lower than 5%. During measurements, "with the proper instrument design, calibrations, and use" the total uncertainty shall not exceed 10%.

III. HALL EFFECT SENSORS (HES)

There is plenty of Hall effect sensors (vane-operated position sensors, linear and closed loop current sensors, mechanically operated solid state switches, gear tooth sensors) sold for a broad range of applications (flow rate, proximity, current, door interlock, crankshaft position, level/tilt measurement, brushless DC motor, magnetic card reader, etc.) [7]. Only a subset of them is suitable for accurate magnetic field measurement for the given amplitude levels and frequency ranges.

A careful search has been carried on with: 1) Internet search of first hand information for each manufacturer and product; 2) location of the target sensors; 3) search refinement and direct inquiries to the respective manufacturers, including quotation. An important discrimination element was also a practical factor: 4) availability of sensor in small quantities. The results have been reported in Table I (some notes are added below the table; Bell sensors were not included because of a ten-times higher price with respect to the other sensors average price) [8]-[14].

TABLE I
LIST OF SELECTED HALL EFFECT SENSORS (AS PER DATASHEET INFORMATION)

Manufact.	Model	Max B [mT]	BW [kHz]	Gain [uV/uT]	Lin. err. %	Temp. [%/°C]	Noise [mV]
Allegro	1321/1323	40/80(1)	30	50/25	1.5	1.0	40/20
Analog Devices	AD22151	50	5	4.0	0.1	0.02	6.8(4)
Asai Kasei	HG106A	300	n.a.	1.7	2.0	-0.06	n.a.
Asai Kasei	HW300A	50	n.a.	4.4	n.a.	-1.8	n.a.
Honeywell	SS495A1	67	20	31.25	1.0	±0.04	n.a.
Honeywell	SS496A1	84	20	25.0	1.0	±0.03	n.a.
Honeywell	SS94A1F	10	100(2)	250.0	1.0	±0.1	n.a.
Honeywell	SS94A2D	250	100(2)	10.0	1.0	±0.02	n.a.
Melexis	MLX90251	600(3)	10		0.2		n.a.
Ohio	HR36	1000	n.a.	0.35	n.a.	-0.1	n.a.

Notes:
(1) not given; estimated from max output voltage swing and gain specifications;
(2) estimated from a "response time = 3 us" specification;
(3) MLX sensor is a digitally programmable sensor, with selectable ranges, the higher one is 600 mT full scale, but resolution is poor;
(4) over 6 kHz bandwidth.

Other important features are: sensor accuracy and stability. The first is intended as compliance of sensor to gain (or transfer function) datasheet specifications and indeed may be considered a second order feature, since its evaluation is included in overall measurement system calibration. On the other hand, stability is a very important parameter: stability is intended as constancy of one sensor parameter with respect to external parameters variation (typ. supply voltage and temperature). It must be underlined that a good design of the conditioning and supply circuitry is able to compensate for not excellent stability: supply voltage stability is ensured by fine voltage regulation and filtering; temperature stability is ensured by internal temperature regulation with warming resistors at the expense of a little extra power consumption. Also offset is not a critical sensor feature, since it may be compensated with an offset compensation circuit placed on the operational amplifiers of the first or second stage of the signal conditioning amplifier.

It must be underlined that in general HES datasheets and information is very poor. Only one manufacturer gives complete noise information, while another one gives a total noise figure over entire bandwidth as peak-to-peak voltage. The characteristics of latest and top performance HES from Honeywell have been initially derived from a technical note by RS (the electronic component supplier) and only after they were found on one of the official Honeywell websites: Honeywell refused to release any further information on these products. So, in author’s opinion a direct measurement and collection of all the characteristics needed for the selection of the best sensor and accurate magnetic measurements is of paramount importance, taking into account also the need for a complete measuring equipment full compliant with ICNIRP specifications.

Honeywell and Ohio Semitronics sensors have been chosen for further analysis. Asai-Kasei are still under investigation (some questions and samples have been asked several times to the manufacturer, but no answer). Analog devices sensor has been chosen as the reference device, since (as usual) Analog Devices datasheet information is complete and clear.

IV. SENSOR REQUIREMENTS

In this Section the specifications reported in Section II are translated into requirements, both for the Hall effect sensors (examined in Section III) and signal conditioning circuitry (no implementation details but only general validity requirements and guidelines).

An imperfect frequency response between dc and 100 kHz (or smaller upper corner frequency, if the specification is de-rated) may be adjusted by proper trimming of signal conditioning circuitry with an internal laboratory calibration procedure of the complete (sensor + circuitry) measuring system. On the contrary, the mDF specification imposes a complete evaluation of sensor output noise, by means of accurate narrowband measurements and, if not possible, broadband time domain measurements. Different bandwidths have been set, based on Section II specifications:

10 Hz: semiconductors $1/f$ noise density is much larger for frequencies below typ. 10-20 Hz and both Hall effect sensors and signal conditioning circuitry are semiconductor made;

2 kHz: for comparison with VDT standard specifications;

100 kHz: for full bandwidth measurement.

V. MEASUREMENT SETUP AND RESULTS

Measurements have been performed on samples with a HP 3563A FFT analyzer (see Table II).

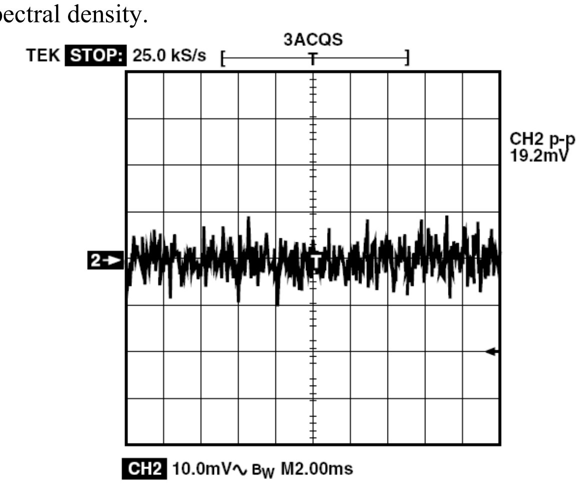
Table II HP 3563A specifications

Parameter/Feature	Value
Frequency range	64 uHz – 100 kHz
Absolute accuracy	±0.25 dB ±0.25% of input range
Noise floor	< 63 nV/sqrt(Hz)

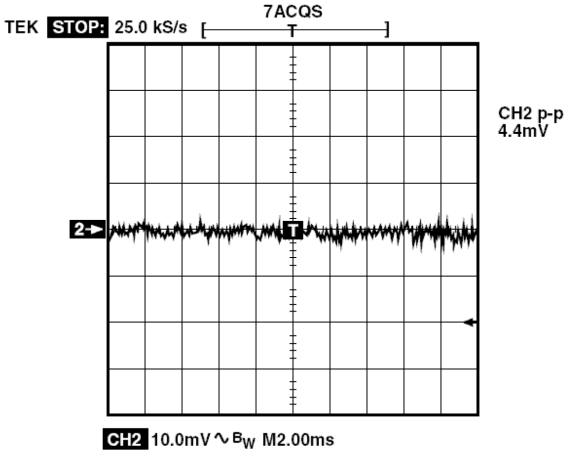
The measurement setup circuit was initially very simple: the HES is supplied at the rated voltage/current and connected directly to the HP3563A input terminal; an optional resistor is placed in parallel if manufacturer specifies a preferred load value (like for SS94 devices), with care not to introduce to much thermal noise with too large resistor values; a decoupling capacitor is place between HES supply terminals to reject any power supply disturbance. Shielded conductors are used to minimize noise pick-up. Noise voltage measurement results are then translated into B-field equivalent noise, taking into account sensor gain [uV/uT].

For some devices, especially HR36, the noise signal is so low that the HES output signal is amplified with a custom low noise amplifier, which is briefly described. It is a three stage amplifier, with a low gain low noise first stage; OPA27 opamp is used, even at low closed loop gain to cope with the reduced gain-bandwidth product, 8 MHz, with respect to OPA37, 63 MHz, but at the expense of larger equivalent input noise (EIN). OPA27 EIN is only 4 nV/sqrt(Hz) above 10 Hz, with about 6-7 nV/sqrt(Hz) at 1 Hz (these specifications changes slightly for OPA27, OP27 and TLE2027 opamps). The overall amplifier gain may be selected as high as 6000.

Since the present work aims to quantify HES noise spectra starting from very low minimum frequency (1 Hz and even down to 0.1 Hz), another important factor must be taken into account: at such low EIN levels, not only additional thermal noise from source and loading resistors must be considered, but also thermoelectric potentials (TPs) due to dissimilar metal junctions (traces, component leads and soldering) [16]. These values are comparable with (and maybe larger than) the opamp EIN and moreover they fluctuate heavily, depending on airflow circulation, due to the most different causes: instrumentation fan, normal laboratory air circulation, movement of persons and objects. At this stage the amplifier was covered with some layers of wool and cotton and a warm-up time of about 15-20 minutes was chosen for each measurement. A thermally regulated and isolated amplifier with optimized layout is under construction to further improve measurement quality. The actual implementation ensures an EIN spectrum produced by TPs fluctuations of only about 30-50 nV/sqrt(Hz) at 0.2 Hz and negligible above a few Hz. This values are approximately in agreement with the time recordings shown in [16], where a peak-to-peak fluctuation of about 0.1 uV in a similar circuit arrangement over a 10 Hz bandwidth: if a flat Power Spectral Density (PSD) spectrum is assumed, this gives a 30 nV/sqrt(Hz) spectral density.



(a)



(b)

Fig. 2. AD22151 noise:
(a) full, (b) 180 Hz bandwidth time-domain signals

With reference to Analog Devices information, the p-p full bandwidth and 180 Hz noise voltage of Fig. 2a and Fig. 2b gives 6.8 and 1.5 mVrms respectively; assuming a flat PSD spectrum, this gives 270 nV/sqrt(Hz) and 8.6 uV/sqrt(Hz) PSD values, and this results reveals that there must be a larger contribution at low frequency, confirmed by the profile of the PSD spectrum: we may conclude for AD sensor that the noise PSD is meaningful up to about to 3 kHz, where it drops by about 3 dB. If these values are compared with HES gain (given in Table I), we obtain an equivalent magnetic noise (EMN) for the results above of 67.5 and 2150 nT/sqrt(Hz) for full and 180 Hz bandwidth.

Preliminary results obtained with time domain measurements for Honeywell SS94A2D gives a PSD of about 500 nV/sqrt(Hz) below 10 Hz. The PSD was then measured in the frequency domain and it was found that it is about 10 uV/sqrt(Hz) at 0.2 Hz and 2.2 uV/sqrt(Hz) at 1 Hz; this translates into 1000 and 220 nT/sqrt(Hz) respectively. The high frequency PSD is pretty flat around about 20-40 nT/sqrt(Hz).

Ohio HR36 was very difficult to treat, since the output signal is very weak (this device exhibits the lowest gain) and the amplifier was set to the maximum gain of 6000. As a consequence also thermal noise and TPs fluctuation noise were of concern and the obtained results are to be considered preliminary (amplifier noise may be reduced as explained earlier): about 150 nV/sqrt(Hz) at 0.2 Hz and down to 30-35 nV/sqrt(Hz) at 1 Hz (at this level total amplifier noise is of concern). Taking into account the HES gain these results translate into about 430 and 85-100 nT/sqrt(Hz) at 0.2 and 1 Hz respectively. Noise is negligibly small at higher frequency: <10 nV/sqrt(Hz) above about 20 Hz and this value is comparable to the total amplifier EIN. At even larger frequency (above about some hundreds Hz) a high pass behavior is encountered, so that the measured PSD starts to increase; the HES output signal increases correspondingly with frequency so that the signal-to-noise ratio seems approximately preserved. However there is no clear explanation for this phenomenon and neither manufacturer's datasheet [14] nor textbooks and publications [7] on the Hall effect subject report something similar.

VI. CONCLUSIONS

Basic requirements in terms of frequency range and dynamic range have been setup following ICNIRP specifications. An extensive search of Hall Effect sensors available on the market for accurate magnetic field measurements have been performed. The need for a complete analysis and performance evaluation of available sensors came from the need for a full ICNIRP compliant measurement system.

The results indicate that some of the examined sensors are suitable for such task, but the subject needs to be more deeply investigated for two reasons: a high performance amplifier is needed to carry on the complete measurements; further testing and theoretical analysis is needed to explain the behavior of one of the examined sensors.

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